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Analysis of Joint URBAN 2003 Wind and Turbulence Profiles and Comparison with FEM3MP Simulations

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Disclaimer

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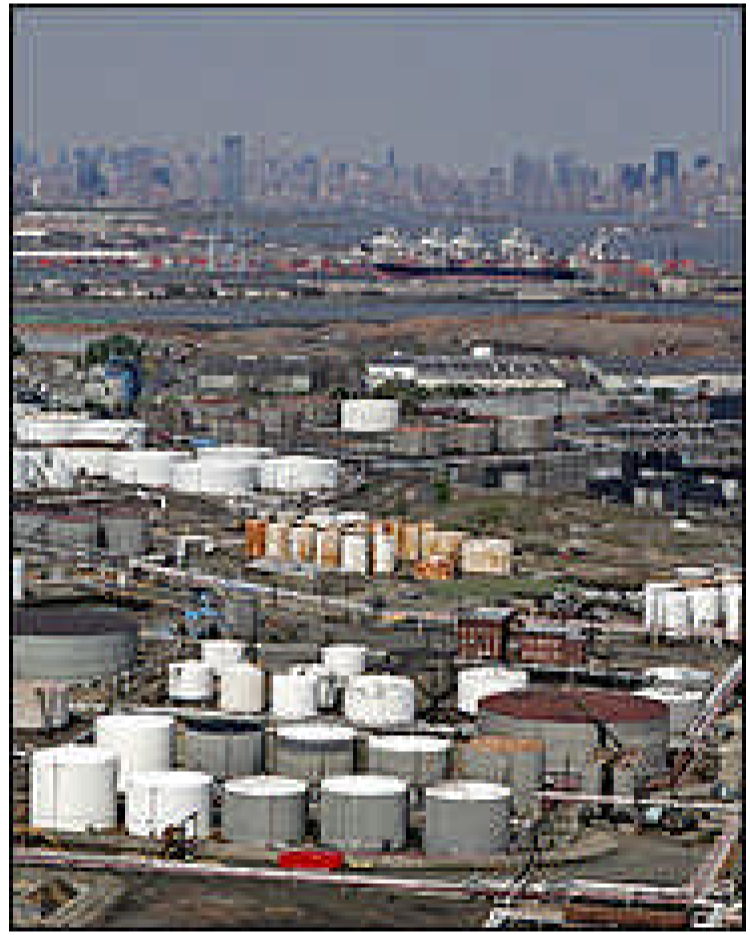
National security demands improved modeling of atmospheric flow in urban environments

- CFD models are currently appropriate for sensor-siting studies or post-event analysis
- Computational shortcuts, like virtual buildings or simplified atmospheric conditions, may make CFD appropriate for emergency-response capabilities if processor speeds continue to increase
- When compared with observations of flow within cities, are CFD results reasonable?

→ Test with Joint URBAN 2003 data on daytime (IOP3) and nighttime (IOP9) releases

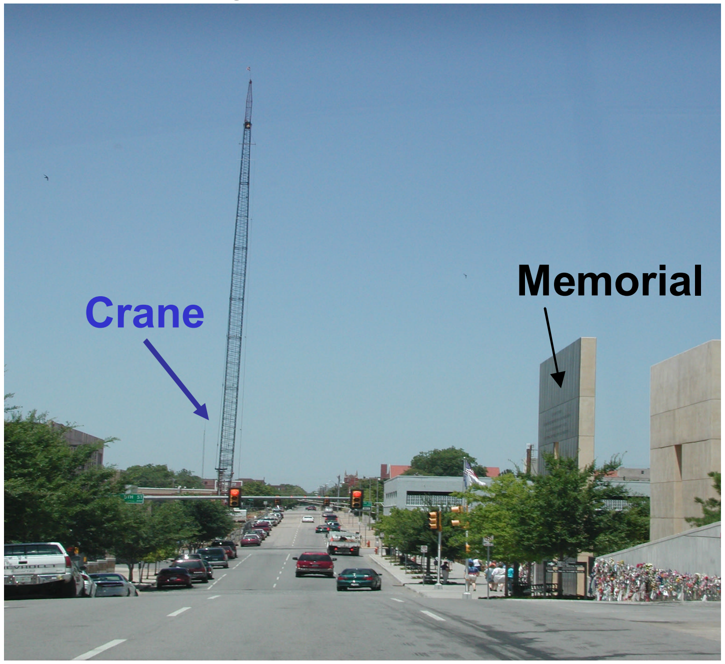


Keith Meyers, New York Times, 9 May 2005: chlorine tanks at Ports Elizabeth and Newark, with Manhattan in the background

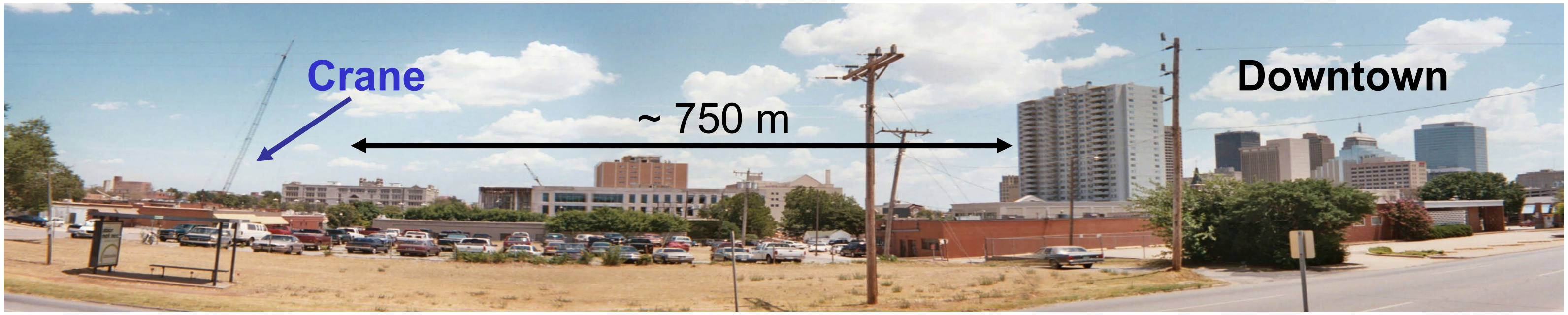
LLNL's crane pseudo-tower provided vertical profiling of high-rate turbulence measurements downwind

- Top of pseudo-tower anchored to crane; bottom anchored to a massive weight to maintain tension and minimize swaying or twisting
- Sonic anemometers (**10 Hz** R. M. Young model 81000) located at 8 levels, 8 – 83m

Looking north from downtown



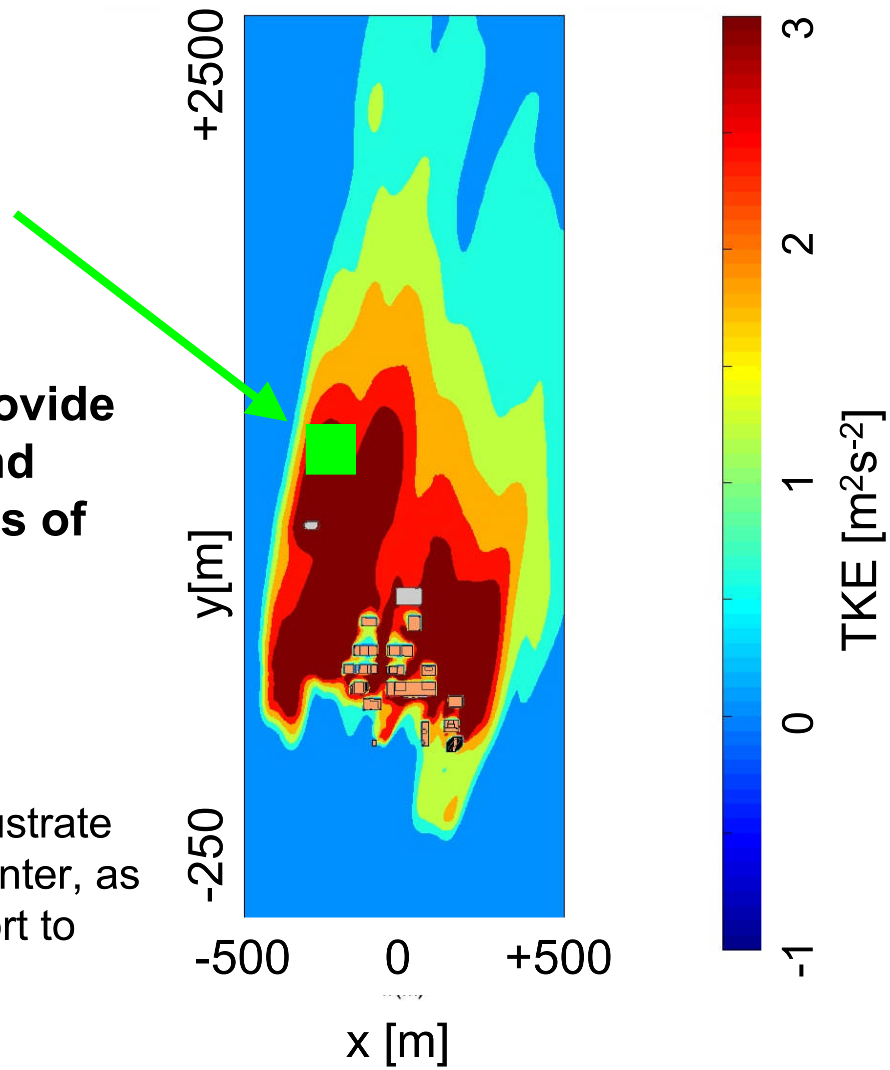
Looking east from westside



Located ~ 750m downwind of the central business district, the crane profile samples the urban wake

Crane is located at ~ (-200, 1200) m in a domain centered at the south edge of downtown (intersection of Broadway and Sheridan).

Eight levels of sonic anemometers provide 10Hz measurements of wind speed and virtual temperature, allowing estimates of fluxes and turbulent kinetic energy.



These contours of TKE at a height of 50 m illustrate the increased production of TKE in the city center, as well as the wake induced by buildings too short to appear in this slice.

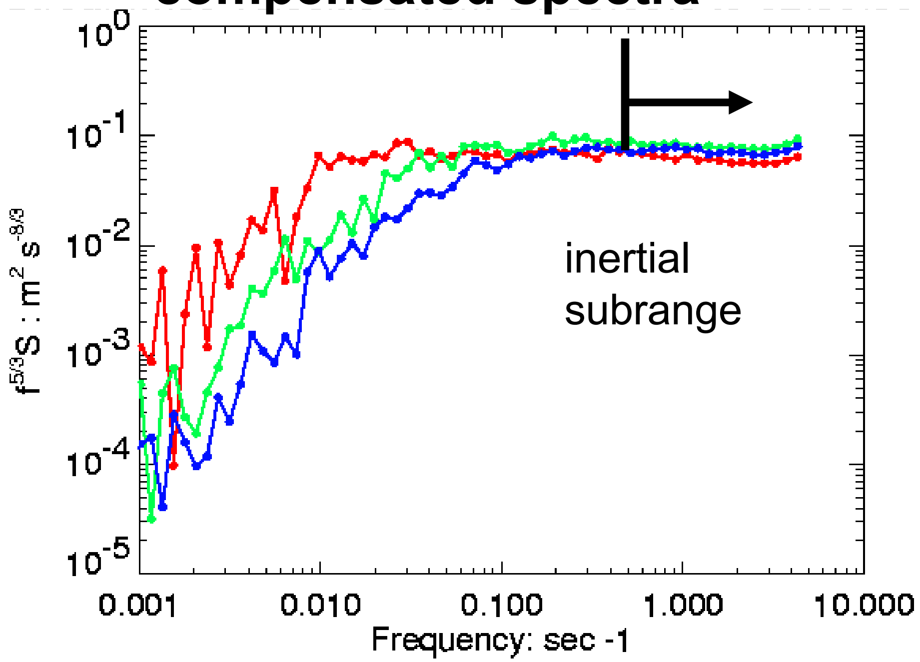
TKE dissipation rate may be estimated from 10Hz sonic anemometer data

- Inertial dissipation method: estimate the dissipation rate based on power (S) in the inertial subrange
- We use average S_u in the inertial subrange, f > 0.5 Hz: by only using one component, we are assuming isotropy
- Inertial dissipation estimation method compares well with direct dissipation calculations (Piper and Lundquist, *J. Atmospheric Sciences*, 2004)

$$\varepsilon = \frac{2\pi}{U}\left(\frac{f^{5/3}S_u(f)}{\alpha}\right)^{3/2}$$

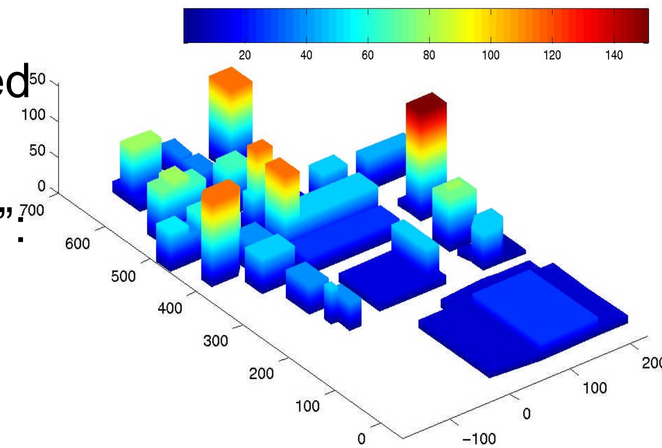
α = 0.52 (Kolmogorov constant)

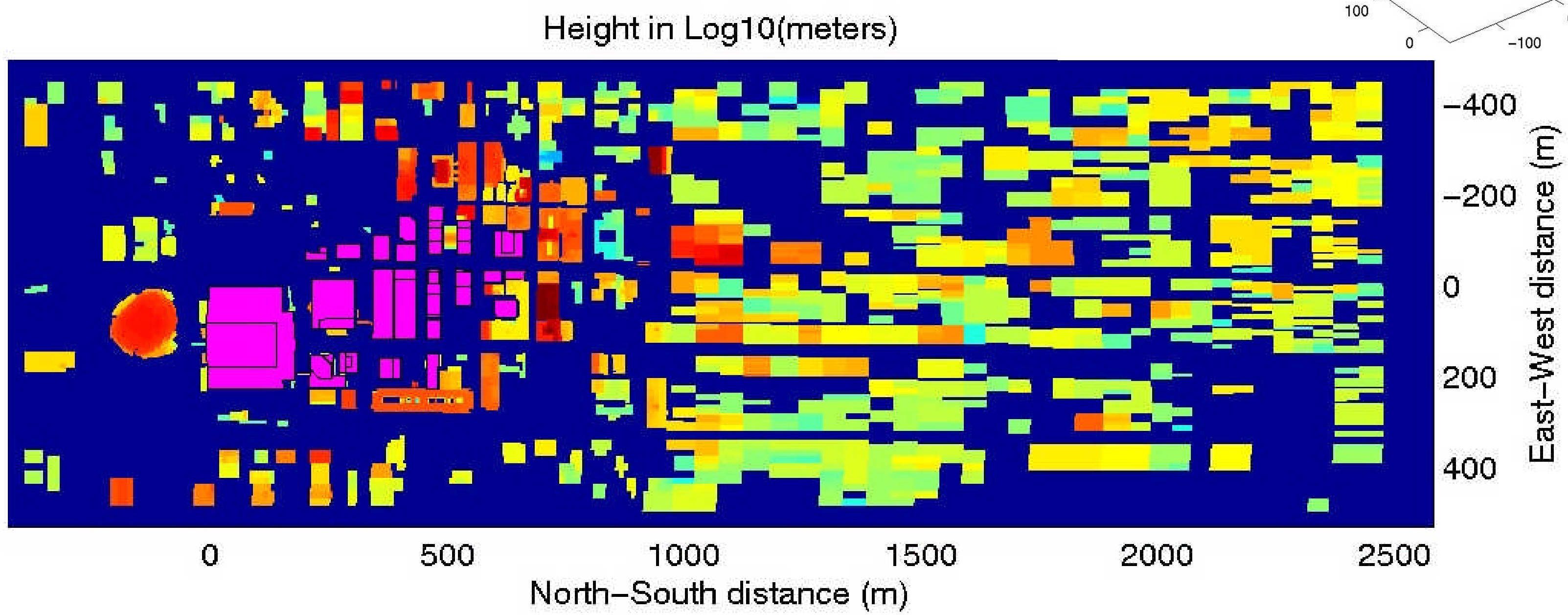
streamwise, transverse, and normal compensated spectra



By using virtual buildings, computational efficiency can be greatly increased

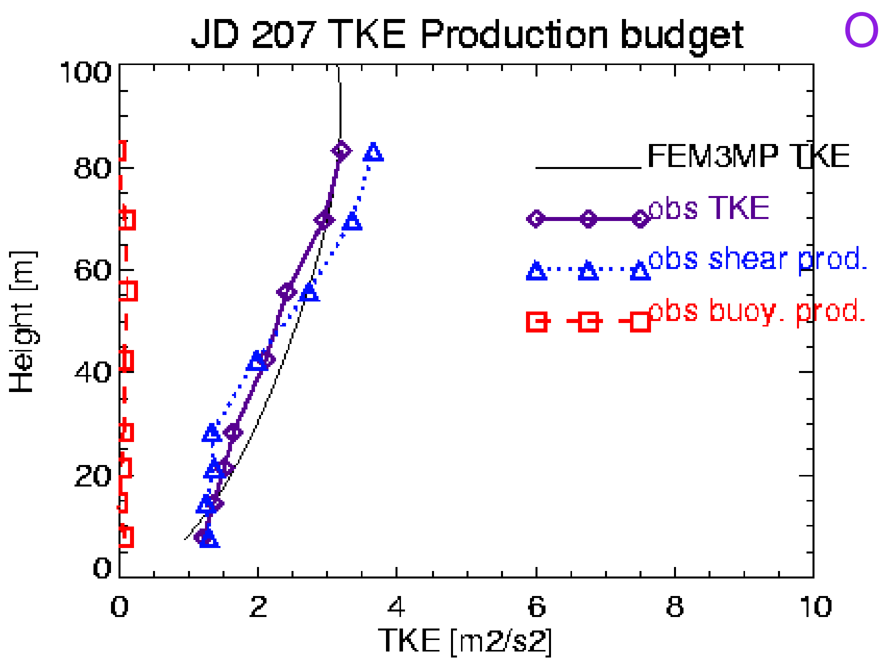
- Buildings within the downtown area are resolved explicitly
- Other buildings are treated as "virtual buildings": elements with increased drag that reflects the height of the buildings





What is the role of buoyant forcing at the crane location for IOP9?

For the nocturnal IOP, we would expect slight anthropogenic heating into a slightly-stably-stratified atmosphere, so a model assuming neutral stability is appropriate.



Observed TKE $= \frac{1}{2}(\overline{u'u'} + \overline{v'v'} + \overline{w'w'})$

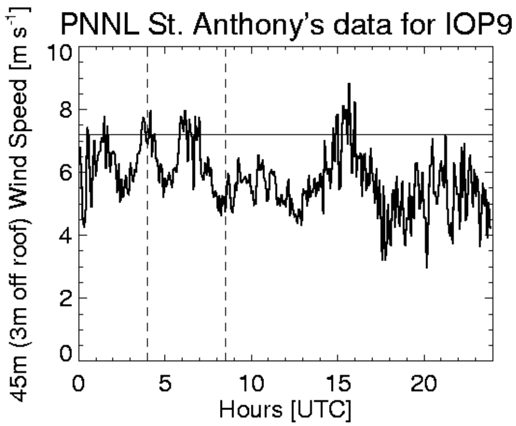
Shear production $= \frac{\partial u}{\partial z}(\overline{u'w'})\tau$

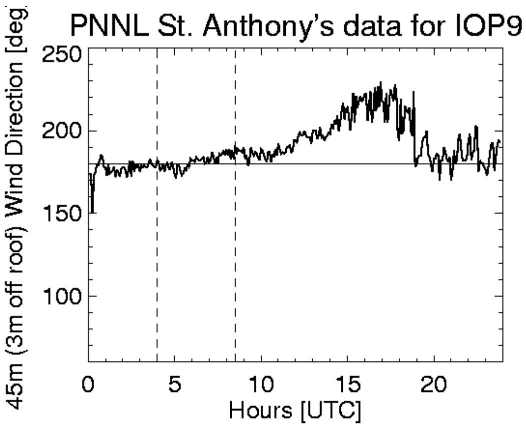
Buoyant production $= \frac{g}{T_o}(\overline{w'T'})\tau$

Timescale τ = 300 sec

Simulation for nocturnal IOP9, with neutral stability, match observations well.

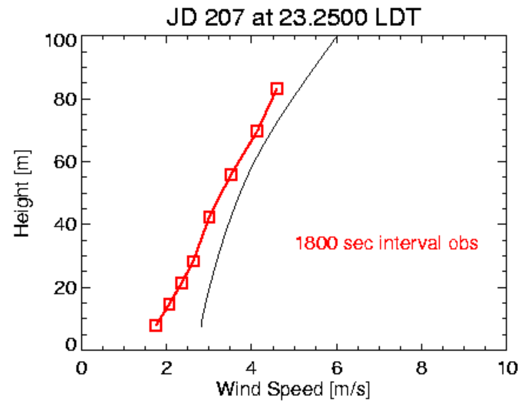
- Inflow conditions: 7.2 m/s wind from 180 degrees

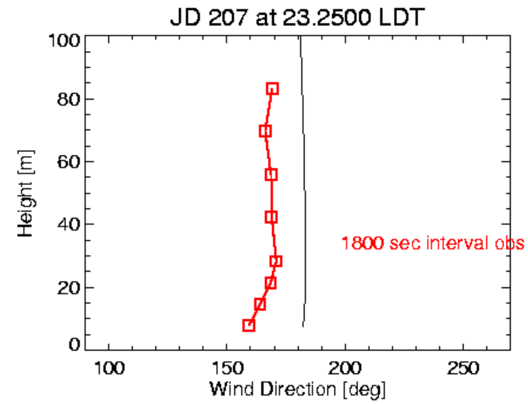


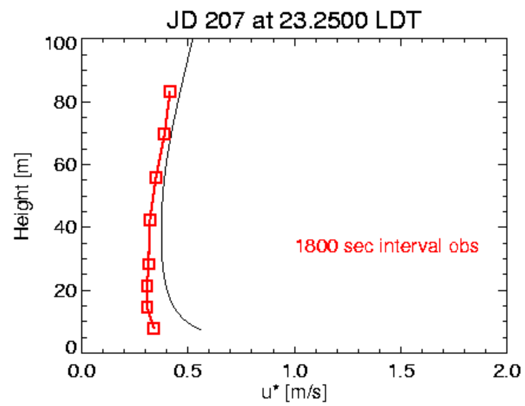


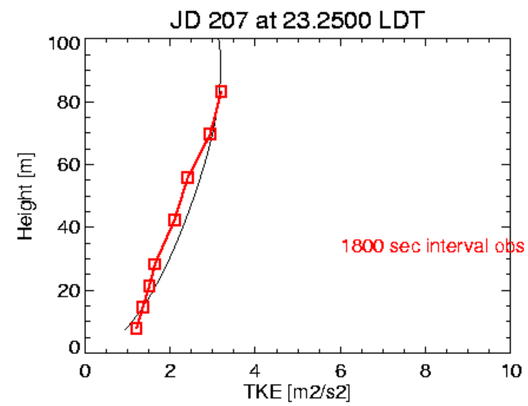
Simulation for nocturnal IOP9, with neutral stability, match observations well.

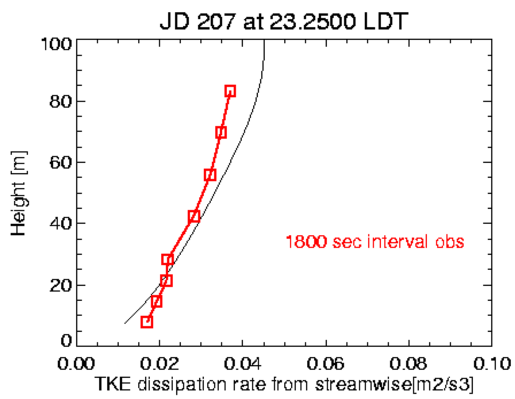
- Inflow conditions: 7.2 m/s wind from 180 degrees
- Observations of TKE show strong shear production of TKE, little buoyant production or destruction
- Wind speed and wind direction profiles are consistent with observations







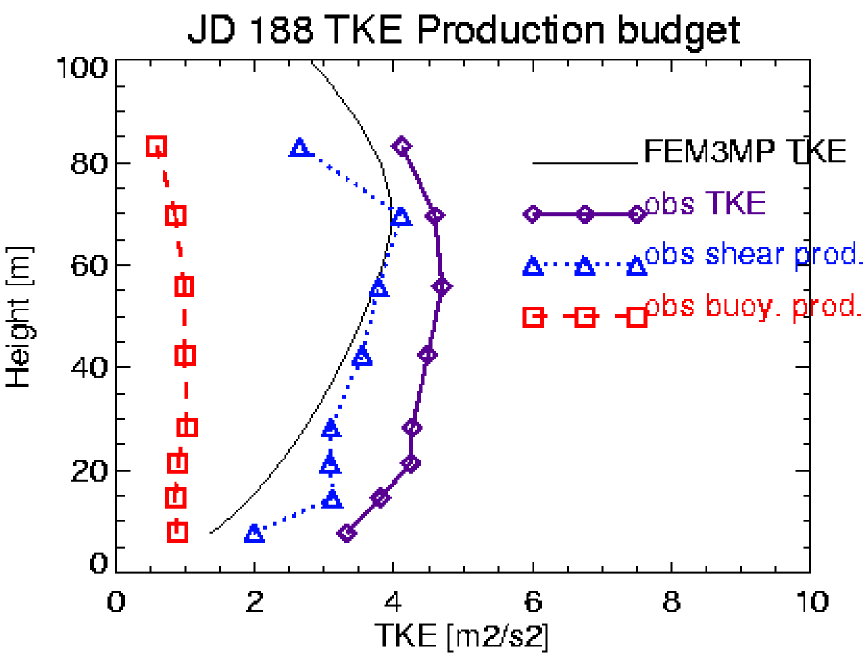




- Friction velocity and TKE profiles match very well, as does TKE dissipation rate profiles

What is the role of buoyant forcing at the crane location for IOP3?

For the daytime IOP, we would expect strong buoyant forcing and strong mechanical mixing. As FEM3MP assumes neutral stability, the “missing” buoyant forcing will be unaccounted for in the model. FEM3MP does capture the shear-generated turbulence well.



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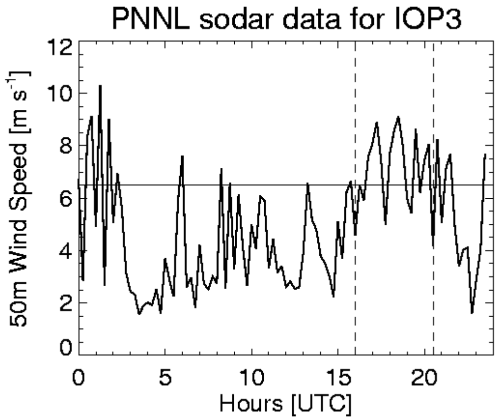
Shear production $= \frac{\partial u}{\partial z}(\overline{u'w'})\tau$

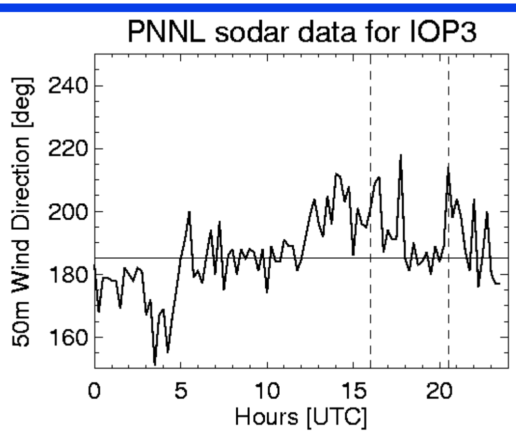
Buoyant production $= \frac{g}{T_o}(\overline{w'T'})\tau$

Timescale τ = 300 sec

Simulation for daytime IOP3, unstable atmosphere:

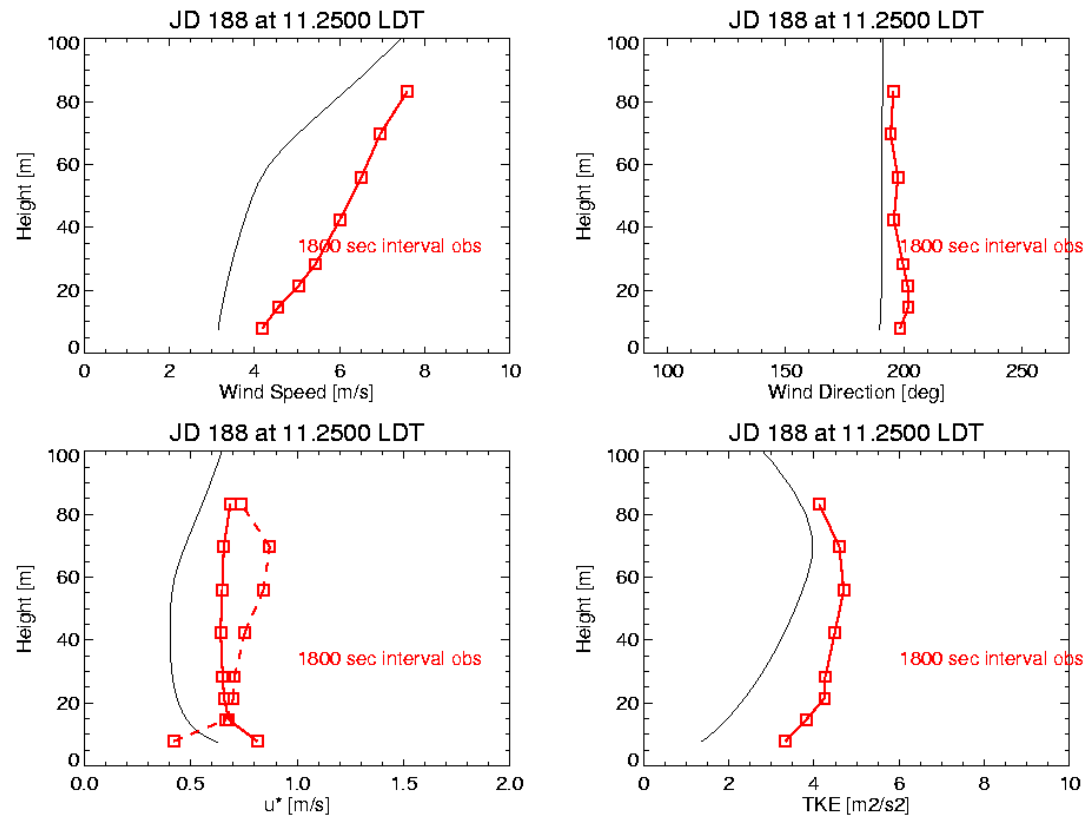
- Inflow conditions: 6.5 m/s wind from 185 degrees

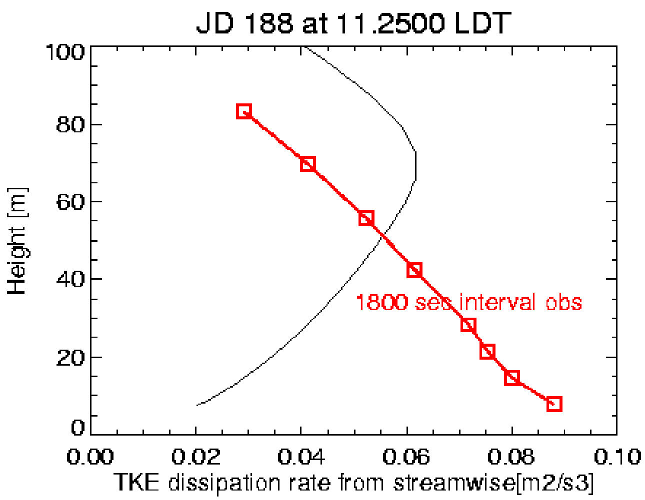




Simulation for daytime IOP3, unstable atmosphere:

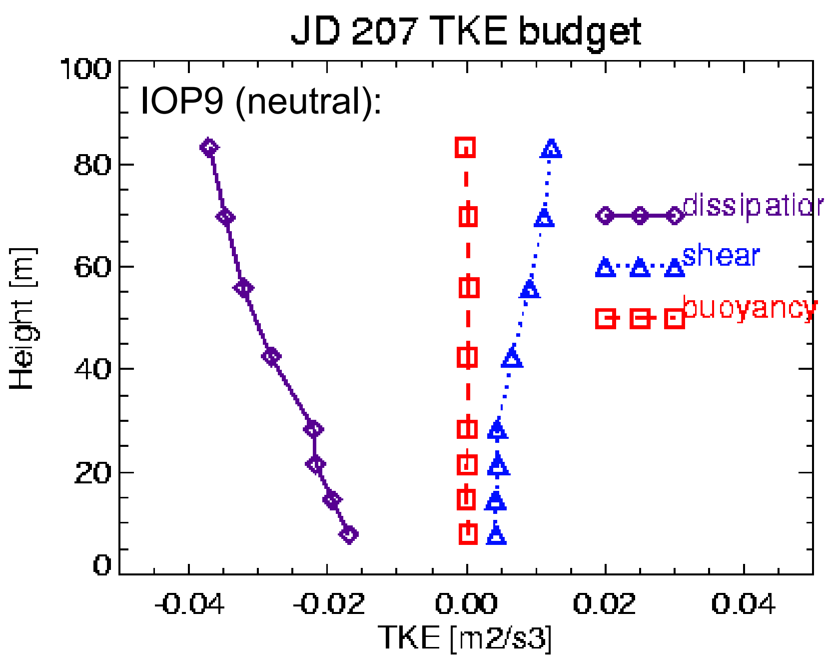
- Inflow conditions: 6.5 m/s wind from 185 degrees
- Observations of TKE show strong shear production of TKE and strong buoyant production of TKE
- Wind speed and wind direction profiles are consistent with observations

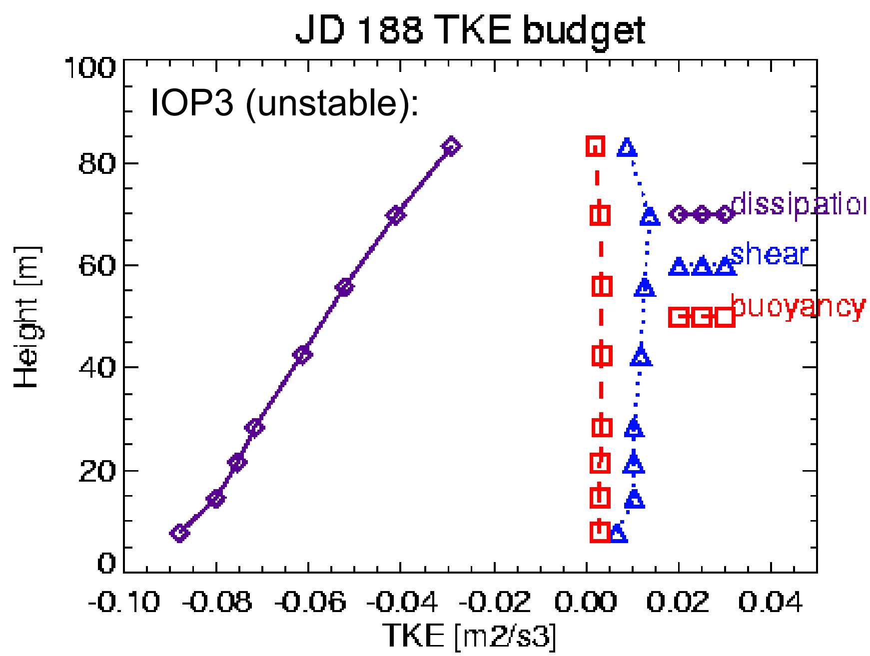




- Friction velocity and TKE profiles are underpredicted, as is TKE dissipation rate, especially close to the surface.

During both IOPs, TKE dissipation at the crane is much greater than local production





- More turbulence is produced within the city center, in the downtown area.
- This urban-core-produced turbulence is advected downwind to dissipate, in the vicinity of the crane.
- Local production of turbulence at the crane is minimal, due to perhaps one or two buildings, and so local production and local dissipation are not balanced.

Intercomparison of data and model output shows:

- The use of virtual buildings (increased surface roughness) may provide a method for increasing computational efficiency while still providing high-fidelity simulations downwind
- At a suburban location 750 downwind of the OKC central business district:
  - the role of buoyant forcing is negligible for RANS simulations during nocturnal conditions, and good agreement between FEM3MP RANS simulations and observations is found
  - for daytime simulations, buoyancy could explain large discrepancies between FEM3MP predictions and observed downwind turbulence profiles
- Turbulence closure models which require balance between turbulence production and dissipation are invalid in the wake of an urban area

Extra slides

Dissipation rates modeled in FEM3MP compare to those observed at the crane